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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2871

EXPERIMENTAL INVESTIGATION OF LOSS IN AN ANNULAR CASCADE
OF TURBINE-NOZZLE BLADES OF FREE VORTEX DESIGN

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SUMMARY

An investigation of the flow pattern immediately downstream of an annular cascade of nozzle blades designed for vortex-type velocity distribution and hub discharge angle of approximately 65° from axial was conducted in order to obtain a better understanding of the processes by which the distribution of losses and deviations from design turning angle occur. For the two Mach numbers investigated, the loss region at the outer shroud decreased while that at the inner shroud increased with increasing Mach number.

The discharge-angle variation was comparatively small over most of the passage, the greatest variation being in the loss region near the inner shroud at the higher Mach number. Despite the size of the loss regions and angle gradients, over-all mass-averaged blade efficiencies were 0.99 and 0.98 in order of increasing Mach number and, therefore, are not a good index of blade performance. Results of the shift of the loss region and visual indications of the boundary-layer flow along the blade surfaces at the higher Mach number showed that the low-momentum fluid originating on the outer shroud and on the blade surfaces flows radially inward through a thickened (or partially separated) portion of the boundary layer on the blade suction surface and along the trailing edge in the wake of the blades; that is, in regions where the resisting shear forces are small or where the local velocities in the main flow direction are small. Indications of the boundary-layer flow by hydrogen sulfide traces on both shrouds showed that the low-momentum fluid in the wall boundary layer, when passing through the blade channel, moves from the pressure side to the suction side of the adjacent blade and rolls up on the suction surface of the blade near the trailing edge.

In the region of high velocity gradients (particularly in the loss regions near the inner shroud and for the higher Mach number), the accuracy in measurements of pressure and flow angle may be limited, and the interpretation of these measurements should be made with care.

INTRODUCTION

As gas velocities through turbines are increased to obtain increased power and increased mass flow per unit frontal area, the three-dimensional aspects of the higher gas velocities become increasingly significant. As transonic velocities are approached, the secondary flows resulting from the radial gradients of pressure, velocity, and circulation become too large to be ignored in the design of turbine blades. Present-day blade design methods are generally based on modified two-dimensional flow theory which neglects these three-dimensional secondary flows and thereby fails to account for a large percentage of the losses in actual turbine operation.

In order to obtain a better understanding of the flow processes within turbines, an experimental investigation is being conducted at the NACA Lewis laboratory on several turbine-nozzle configurations which are typical of modern turbines. A study of the flow processes through an annular cascade of nozzle blades having a vortex-type velocity distribution is described herein. Detailed data, including surveys of total pressure and discharge angle in the free stream, wake, and boundary layer at hub discharge Mach numbers (adjacent to the boundary layer) of 0.94 and 1.46 (hereinafter referred to as lower and higher Mach number, respectively), have been taken of the flow immediately downstream of the set of nozzle blades. As a means of obtaining a visual picture of the flow along the blade surfaces and shrouds, hydrogen sulfide and paint traces of the flow direction were taken by the method given in reference 1.

APPARATUS

Test unit. - A schematic view of the test unit used in this investigation is shown in figure 1. A filter was installed in a large depression tank (not shown in fig. 1) upstream of the test section to prevent damage and clogging of the delicate instruments by dirt particles from the air supply. The filter consisted of two layers of 1/4-inch felt separated by filter paper with both supported by wire mesh screening. A second depression tank downstream of the first tank was located approximately 4 duct diameters (approximately 6 ft) upstream of the nozzle blades (fig. 1). A long-radius nozzle was installed in the depression tank to provide smooth entry into the duct leading to the nozzle blades in the test section. A fine mesh screen was also installed in the tank to give a uniform inlet velocity distribution. The air discharged from the nozzle blades into an annular duct having six straightening vanes located approximately 3 tip diameters downstream of the nozzle blades.

Nozzle blades. - The nozzle blades used in the investigation were designed for a free vortex-type velocity distribution with a discharge

angle of approximately 65° from axial at the inner shroud and an equivalent weight flow of approximately 15.3 pounds of air per second. The blades were designed by the two-dimensional stream filament theory described in reference 2. As the stream filament applies only to the portion of the blades forming the channel, the greatest portion of the turning was done in the channel. The trailing-edge portion of the blade having little curvature was faired at the approximate turning angle. Comparison of the design circulation with the two test Mach numbers is shown in figure 2. The design circulation compared favorably with the lower Mach number test as the mass-averaged hub Mach number was approximately equal to that at design.

The 48 blades of the turbine-nozzle cascade have a hub-to-tip radius ratio of 0.730, with a tip diameter of 16.25 inches. The blades have a solidity of 1.507 at the hub and 1.595 at the tip. The blade chord and trailing-edge thickness vary from respective values of 1.696 and 0.044 inches at the tip to 1.172 and 0.034 inches at the hub. Blade profile and stacking coordinates are given in table I.

INSTRUMENTATION

The cascade was instrumented to obtain surveys of total and static pressures at the inlet measuring station located 0.5 inch upstream of the leading edge of the tip section of the blades. Total pressures, wall static pressures, and flow angles were surveyed at the discharge measuring station located 0.159 inch downstream of the trailing edge of the nozzle blade tip. The instruments used to obtain the detailed surveys of the gas state at the inlet and discharge are shown in figure 3.

Total-pressure measurements. - Two types of total-pressure probe were used to measure total pressure at the discharge measuring station: one type was designed specifically for measurements in the boundary layer; the other, for free-stream measurements.

The pressure-measuring head of the boundary-layer probe (fig. 3(a)) consisted of 0.015-inch-outside-diameter tubing. The tip was flattened to approximately 0.003-inch inside minor axis length (parallel to probe axis) to obtain closer approximations of point values in the regions of high radial pressure gradients.

The three-dimensional total-pressure probe (fig. 3(b)) was designed to measure the total pressure outside the boundary layer for radial flow angles within the limits of approximately $\pm 9^\circ$. The probe consists of five 0.015-inch-outside-diameter tubes projecting 0.120 inch from the probe axis. The tubes are set at angles of 3° , 6° , -3° , -6° , and 0° from a plane normal to the axis of the probe and with the measuring ends of the tubes in this plane.

A shielded total-pressure probe was used to measure the reference total pressure at the inlet to the blades.

Static-pressure measurements. - Wall static taps of 0.015-inch diameter were located at both the inner and outer shroud in the inlet and discharge measuring planes. At the inlet measuring plane, one static tap each at the inner and outer shrouds was located at the circumferential position used for the inlet radial surveys.

Angle measurements. - A double-wire hot-wire-anemometer probe (fig. 3(c)) was used to measure the discharge flow angles in the main stream. The instrument consists of two parallel wires, supported by two prongs and mounted under tension on the axis of the probe (parallel to a radius of the cascade). Thus, the wires can be rotated without appreciable displacement. Each of the wires has a diameter of approximately 0.0009 inch and a length of 0.045 inch or less. The distance between wire centers is 0.005 inch.

For use in the inner-shroud boundary layer a V-wire type of hot-wire anemometer (fig. 3(d)) was constructed, having the two wires mounted in such a way that both were in the same plane and parallel to the shroud surface (perpendicular to a radius of the cascade) when in use. The wires of this instrument have a diameter of 0.0011 inch and a length of 0.050 inch. They were mounted on three supports, the tips of which were located at the corners of an equilateral triangle. Thus, the two wires mounted near the support tips formed a V with a 60° angle at their intersection. The use of such an instrument near the inner shroud was based on the assumption that no steep circumferential gradients of angle or pV would be present.

Details of design of wire supports and the general construction of the hot-wire probes is discussed in reference 3. The application of hot-wire-anemometer probes to the measurement of discharge flow angles for the flow conditions reported in this investigation is discussed in appendix A.

A double-tube pressure probe (fig. 3(e)) also was used for angle measurements in the boundary layer. In order to minimize effects of pressure gradients and angle gradients on the measured angle, the tube dimensions were made small. Each tube was of 0.010-inch-outside-diameter stainless steel. The tubes were soldered together and mounted in such a way that the double open end had its axis lying in a circumferential plane and could be rotated about a radial axis. In order to increase the sensitivity to flow direction, each tube end was ground back at an angle of 30° from the soldered tip junction so that the tip was wedge-shaped with a 60° total angle.

Repeatability. - Discharge total pressures in the free stream, wakes, and boundary layers and wall static pressures could be repeated within ± 0.05 inch of mercury during any extended time interval. The reproducibility of ± 0.05 inch was maintained by observing the data when the reference static pressure was steady at the desired set value.

The flow angle measurements made with any given probe could be repeated within $\pm 0.5^\circ$ with that probe. At the lower Mach number the two boundary-layer angle probes gave data which resulted in contour lines of approximately the same shape. Maximums and minimums were in the same positions and had the same magnitudes to about $\pm 1.0^\circ$. V-wire data from the boundary layer could be faired into parallel-wire data from the main part of the annulus with adjustments of not more than about $\pm 1.0^\circ$.

Agreement between probes was not so close at the higher Mach number because of the higher gradients in angle and mass flow encountered. These gradients have effects on one type of probe different from those on another. The two boundary-layer probes showed angle gradients in the same direction over much of the region where they were used, but the magnitudes of the gradients were not in agreement. However, at this Mach number the pressure-probe angle data were in moderately good agreement with parallel-wire data in the region where the data overlapped. Therefore, pressure-probe angle data were used to make contours between points 0.005 and 0.080 inch from the inner shroud, and parallel-wire data between the outer shroud and points 0.120 inch from the inner shroud. Contours were then faired in between 0.080 and 0.120 inch from the inner shroud.

PROCEDURE

Radial surveys of total and static pressure were made at the inlet measuring station, and circumferential and radial surveys of total pressure and flow angle were made at the discharge measuring station for each of the two Mach numbers. In addition, studies of surface flow direction were made at both Mach numbers. The reference inlet total pressure was held constant at 26.50 inches of mercury absolute, and the inlet total temperature was maintained at 553°R for all surveys.

Inlet surveys. - Radial surveys of total pressure and static pressure were made at only one circumferential location at the inlet, because preliminary surveys indicated little measurable circumferential variation in either total or static pressure. One static tap each on inner and outer shrouds furnished the static-pressure values for the end points. Preliminary angle surveys indicated little variation from the axial direction over the blade passage, and the inlet velocity distribution was therefore satisfactory for the investigation.

Discharge static pressure. - Wall static-pressure values for the nozzle discharge were obtained from the static taps located in the discharge measuring plane. For purposes of velocity calculations, static pressure was assumed to vary linearly from inner to outer shroud.

Discharge total-pressure surveys. - At the discharge measuring station, circumferential surveys of total pressure were made covering an arc corresponding to one complete passage with some overlap. These surveys were spaced radially in such a way as to cover boundary layers and loss regions in detail, and at the same time to survey other regions closely enough to verify the existence of uniform flow. Circumferential points were likewise spaced so as to give detailed information in loss regions and wakes. Determination of the radial position of the probe within 0.002 inch in the annulus behind the blades was required in order to locate accurately the wakes, boundary layers, and loss regions with respect to the walls. For this reason, the inner shroud as a reference position was located by use of a low-voltage electric circuit which indicated by a light when contact was made between the measuring probe and the inner shroud.

Free-stream total pressures were measured with the five-tube total-pressure probe. Each of the five tubes was rotated into the stream for a maximum reading, and the greatest total-pressure reading obtained from the readings of any of the five tubes was taken as the total-pressure value for the survey point.

At the higher Mach number the free-stream flow was such as to produce a normal shock upstream of the total-pressure probe. The measured total pressure under such conditions might be corrected to give the free-stream total pressure. However, such a correction requires knowledge of static pressure as well as measured total pressure at the point in question. Static pressure is not known accurately except at the walls for the present investigation. Attempts to use interpolated static-pressure values for this purpose resulted in some cases in corrected total pressures larger than the inlet total pressure, which indicated that, in these cases, the corrections are erroneous. This may be due to improper static-pressure interpolations or incorrect assumptions about the nature of the shock. The shock upstream of the total-pressure probe for some locations may have been not a normal shock, but one complicated by the presence of boundary layers or loss regions in the vicinity. Hence, it was considered advisable to leave the total-pressure values uncorrected.

Discharge-angle surveys. - Surveys of discharge angle were made covering the same blade passage as was covered with the total-pressure surveys. In the free-stream part of the annulus, where it was assumed that high angle gradients or ρV gradients, if any, would be largely

circumferential (as in the blade wake) rather than radial, the parallel-wire anemometer was considered to be applicable. In the shroud boundary layers, where it was assumed that such gradients would be largely radial rather than circumferential, the V-wire anemometer would appear to be more suitable. Actually, the parallel-wire instrument performed well wherever used, and measurements were made with it from the outer shroud to points 0.1 inch from the inner shroud. Near the outer shroud it served to confirm the existence of a steep radial angle gradient; but since the area involved in this loss region was comparatively small, it was given no further attention, although the accuracy might have been improved by use of the V-wire probe.

Near the inner shroud the parallel-wire probe could not be used, not only because of diminished accuracy but also because the distance between survey point (considered as the wire center) and surface was limited to about 0.035 inch. Therefore, data were taken with the V-wire anemometer in the region within 0.2 inch of the inner shroud. These data were satisfactory at the lower Mach number; but at the higher Mach number circumferential gradients of angle and ρV were sufficient to require the use in this region of the double-tube pressure probe, the results from which would be less susceptible to the effects of such gradients.

Surface flow-direction studies. - Visual studies of flow direction along the blade and wall surfaces were made in two ways (reference 1). The first technique used the reaction between white lead carbonate painted on the surface and hydrogen sulfide gas which was admitted through an appropriately located wall static tap and mixed with the boundary-layer air flowing through the cascade. The resulting darkening of the lead carbonate showed the direction of flow along the surface from the static tap. The hydrogen sulfide gas pressure was adjusted to exceed the static pressure at the tap by only enough to cause it to flow into the passage without blowing it away from the surface and without upsetting local flow conditions. The second technique involved softening the lead carbonate with glycerin until it would flow slightly along the surface because of viscous effects between air and paint. A comparison between results obtained by these two techniques showed good agreement; hence patterns on the surface were considered to indicate air-flow direction and the results were recorded photographically.

RESULTS AND DISCUSSION

Results are presented in terms of loss and turning-angle distributions. Indications of the secondary flow and the radial displacement of low-momentum fluid are shown by paint and hydrogen sulfide traces made through the blade channel.

Inlet-pressure surveys. - The results of surveys taken at the inlet measuring station for the higher Mach number are shown in figure 4. Constant total pressure was obtained over the greatest portion of the flow passage, with the losses in total pressure occurring in the wall boundary layers at the blade inner and outer shrouds. The combination of constant total pressure, static pressure, and flow angle produced an inlet velocity distribution which was considered satisfactory.

Discharge surveys. - At the discharge measuring station the Mach numbers were 0.94 and 1.46 adjacent to the inner-shroud boundary layer and 0.75 and 1.06 adjacent to the outer-shroud boundary layer. Results of the total-pressure surveys and static-pressure-tap data are presented in figure 5 as contours of loss, which is defined as follows:

$$\text{Loss} = 1 - \eta = 1 - \frac{v^2}{v_1^2} = \frac{\left(\frac{p}{P}\right)^{\frac{\gamma-1}{\gamma}} - \left(\frac{p}{P_1}\right)^{\frac{\gamma-1}{\gamma}}}{1 - \left(\frac{p}{P_1}\right)^{\frac{\gamma-1}{\gamma}}}$$

The symbols are defined in appendix B.

The figure calculated as loss, therefore, is dependent upon point values of static and total pressures measured at the exit of the blade row.

It is to be noted that circumferential coordinate values plotted in figure 5(b) are slightly different from those plotted in figure 5(a). This was done in order to show a complete blade wake as a unit and is a composite of measurements made in different parts of two adjacent wakes.

Negligible losses were obtained over most of the flow passage. The major losses were observed in the shroud boundary layers, in the blade wake, and particularly along the junctions of the shroud boundary layers and the blade wake. The losses in the blade wake were small compared with those measured in the other loss regions and shroud boundary layers. Maximum losses occurring were 16.2 and 14.3 percent at the inner and outer shroud, respectively, for the lower Mach number run, and 25.2 and 5.3 percent, respectively, for the higher Mach number run. The results show a decrease in loss at the outer shroud with increased Mach number and an increase in loss at the inner shroud with increased Mach number. The changes in the loss picture with Mach number at any radial position are shown in figure 6, for which a loss parameter was mass-averaged circumferentially across a blade passage and was plotted against radius.

The data taken in this investigation were used to obtain blade efficiencies. Mass-averaged blade efficiencies were 0.99 and 0.98 in order of increasing Mach number. Although the mass-averaged blade efficiencies are high, they are not a good index of blade performance. Accumulation of the losses at the junction of the blade and inner shroud, where the velocity gradients are great, could make the flow unstable and induce additional viscous losses and angle gradients.

The results of the discharge-angle surveys are shown in figure 7 as contours of discharge angle. Angle gradients for the lower Mach number (fig. 7(a)) were comparatively small. However, the angle gradients increased with increasing Mach number. The variation in discharge angle across the passage at a radial distance of 0.2 inch from the inner shroud was found to increase from 3.5° for the lower Mach number to 13.6° for the higher Mach number. At the higher Mach number (fig. 7(b)) the greatest variation in discharge angle occurred near the corner of the passage bounded by the pressure side of the wake and the inner shroud.

In order to determine the effect of the angle variation, calculations of rotor-blade angles of attack were made for the higher Mach number where the circumferential angle variations were the greatest. For these calculations, a tip speed of 640 feet per second was assumed. Discharge-flow-angle variations of 13.6° , 5.4° , and 4.0° at radial distances from the inner shroud of 0.2, 1.0, and 2.0 inches, respectively, led to local variations in the rotor-blade angle of attack of 16.9° , 6.6° , and 11.3° . An effect of this variation as discussed in reference 4 was a loss (calculated at a radial position 0.2 in. from the inner shroud) of 1.5 percent of the energy based on tangential component of velocity. Further losses of significant magnitude may also exist because of the effect on the rotor of pulsating flow caused by the variations in nozzle discharge angle.

Discharge-angle distribution. - In figure 8 the circumferential average of discharge flow angle is plotted against radius for each of the two Mach numbers. The measured angles show that in the central part of the passage the turning had approximately design value but that as either wall was approached, there appeared a decrease in discharge angle relative to design value. Near the hub this decrease was more pronounced for the higher Mach number than for the lower Mach number. The reverse was true for the decrease near the outer shroud. This is attributed to a combination of Prandtl-Meyer expansion and increased accumulation of low-momentum fluid near the inner shroud at the higher Mach number, which effectively blocked the flow and induced high axial velocities in the immediate vicinity. The latter effect is discussed more fully in reference 5. Also, at points nearer the walls the discharge angle increased, showing overturning in the boundary layers at the measuring station.

Secondary flow. - When fluid in a cascade is turned, there must be a pressure gradient present to balance the centrifugal force on the particles of the fluid moving through the cascade. In the shroud boundary layers, the fluid has a lower velocity and therefore requires a smaller pressure gradient to balance the centrifugal force. As the free-stream pressure gradient exists almost unchanged in the boundary layers, where shear forces and centrifugal forces are small, a deflection of the flow toward the low-pressure side of the passage is induced.

The result of this motion is a thinning of the shroud boundary layers at the pressure surface and a thickening at the suction surface, where a tendency toward the formation of regions of low-momentum fluid occurs and where the tendency for flow separation is greatest.

The loss contours shown in figure 5 indicate the boundary layers to be thinnest on the pressure side of the wake and thicker toward the suction surface along both shrouds. A visual picture of the accumulation of this low-momentum air in the corner between shroud and suction surface is shown in figure 9. The dark hydrogen sulfide trace appearing between the blades in the view from the inlet side shown in figure 9(a) indicates the source of the gas to be a static tap near the pressure surface at the leading edge. This view is at the inner shroud; a source at the outer shroud was in a similar position. Figure 9(b) shows the hydrogen sulfide trace from downstream as it rolls up with the low momentum air on the suction surface of the blade at the inner shroud, having traversed the passage in the boundary layer from its source near the pressure surface of the adjacent blade. Similar results were found at the outer shroud, as shown by figure 9(c) in a downstream view of the trailing edge of the blades at the intersection of their tips with the shroud.

Just as the cross-channel pressure difference induces a deflection of the flow toward the low-pressure side of the passage, so the pressure difference existing between outer and inner shrouds can be expected to induce radial flow through blade boundary layers and wakes. The area available for such flow, where through-flow velocities are low enough to allow time for appreciable radial movement, is extremely small over most of the blade surface, particularly at the lower Mach number. However, at the higher Mach number the likelihood is much greater for shock - boundary-layer thickening and flow separation at the blade surfaces to provide paths for radial flow of low-momentum fluid. The loss contours of figure 5 indicate a radially inward shift of the major loss region from the outer part of the passage to the inner with increasing Mach number. Visual paint traces of the flow obtained in the cascade give strong indications of the existence of inward radial flows, as well as where they take place. Figure 10 shows for the higher Mach number a line of flow discontinuity (or shock) along the outer shroud from the trailing edge of the pressure surface across the channel, continuing

inward along the suction surface of the adjacent blade. The intersection of the flow discontinuity and the boundary layer on the suction surface of the blade results in a thickened boundary layer. The low viscous shear forces in the thickened boundary layer and the presence of a radial pressure gradient provide a region and inducement for the inward radial flow of low-momentum fluid from the outer to the inner shroud.

Indications of the inward radial flow of low-momentum fluid for the high Mach number run are shown in figure 11(a), a photograph of the intersections of the inner shroud with the trailing edges and suction surfaces of the blades. Six of the blades were treated with paint at suitable locations. For blade 1, paint was applied at the midsection of the suction surface. The paint traces indicate flow of low-momentum fluid inward along the trailing edge and along the suction surface and its build-up of the suction side of the blade near the inner shroud. Blade 2 shows the results of painting the midsection of the pressure surface of the blade. Low-momentum fluid moves from the pressure surface of the blade to the trailing edge and passes inward along the trailing edge with a consequent roll-up near the inner shroud on the suction surface of the blade. Blades 3 and 4 were painted on the suction and pressure surfaces, respectively, near the inner shroud. Blade 3 shows little trace of flow as the low-momentum fluid accumulates in the same region as that where paint was applied. However, blade 4 shows that fluid moves around the trailing edge and accumulates on the suction surface. The radial inward flow of low-momentum fluid from the outer toward the inner shroud along the trailing edge and along the line of flow discontinuity is shown on blade 5, where all the paint flow originates at the suction side of the blade tip. The accumulation of the low-momentum fluid from the pressure side of the blade near the tip is shown in the flow pattern on blade 6. This fluid moves inward along the blade trailing edge and accumulates on the suction side of the blade at the inner shroud.

An enlarged view of the inward radial movement of the low-momentum fluid at the higher Mach number is given in figure 11(b). Suction surfaces and trailing edges are shown. In the tests made for this photograph, three blades were involved. Strips of paint were applied to the suction surfaces of the blades near the inner shroud, at the midsection, and near the outer shroud. The paint traces represent the flow of low-momentum fluid in the thickened boundary layer resulting from the intersection of blade surface and flow discontinuity, as well as flow along the trailing edge of the blade in the wake. The pattern also shows evidence of backflow in part of this region.

The shift of the major loss region from the outer part of the passage to the inner with increasing Mach number and the paint traces of flow at the higher Mach number give good indications that low-momentum

fluid originating on the outer shroud and on the blade surfaces flows radially inward along the line of flow discontinuity as well as along the trailing edge in the blade wake. The radial inward motion of the low-momentum fluid is accomplished by the reduced viscous shear forces in the thickened boundary layer and the presence of the radial pressure gradient.

SUMMARY OF RESULTS

The following results were obtained in an investigation of an annular cascade of turbine-nozzle blades designed for a free vortex-type distribution of velocity with a discharge angle of approximately 65° and tested at hub Mach numbers of 0.94 and 1.46:

1. High loss regions were found at the junction of the blade wakes and shroud boundary layers for the two Mach numbers investigated.

2. The over-all integrated blade efficiencies were found to be 0.99 and 0.98 in order of increasing Mach number. Although these efficiencies are high, they are not a good index of blade performance, as the high loss regions and angle gradients occurring along the suction side of the blade and inner shroud where diffusion is the greatest could result in flow instability and induce additional viscous losses and angle gradients.

3. Angle gradients were found to be small for the lower Mach number run; however, they increased with increasing Mach number. Circumferential angle gradients of 13.6° , 5.4° , and 4.0° at radial distances of 0.2, 1.0, and 2.0 inches from the inner shroud, respectively, led to local variations in rotor-blade angle of attack of 16.9° , 6.6° , and 11.3° for the higher Mach number run.

4. The major shift in loss from the outer part of the passage to the inner with increasing Mach number and the visual paint traces obtained at the higher Mach number indicated that low-momentum fluid originating along the outer shroud and on the blade surfaces flows radially inward along the line of flow discontinuity on the blade suction surface as well as along the trailing edge in the wake of the blade and piles up on the suction side of the wake near the inner shroud. Visual indications of the boundary-layer flow by hydrogen sulfide traces on both shroud surfaces showed that the low-momentum fluid moves from the pressure surface to the suction surface of the adjacent blade when passing through the channel and then rolls up on the suction surface of the blade near the trailing edge.

5. In the region of high velocity gradients (particularly in the loss region near the inner shroud and for the higher Mach number) the accuracy in measurements of pressure and flow angle may be limited, and the interpretation of these measurements should be made with care.

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Lewis Flight Propulsion Laboratory
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APPENDIX A

APPLICATION OF HOT-WIRE-ANEMOMETER PROBE

Parallel-wire probe. - The hot-wire probe for measuring flow angles in the main part of the air stream consisted of two wires of 80 percent platinum and 20 percent iridium mounted in spatial and electrical parallelism. The wires were supported on two Inconel prongs with their lengths perpendicular to the air stream and parallel to the axis of the probe and rotation. The alinement of the wires with the air stream was detected electrically by observing the maximum in potential drop when the downstream wire temperature reached a peak as a result of receiving heat by convection through the wake from the upstream wire.

The electrical equipment used for the discharge-flow-angle investigation with this hot-wire-anemometer probe consisted essentially of a bridge circuit, a direct-current power supply with which the current could be easily adjusted over a continuous range, a direct-current voltage amplifier, and a voltmeter for indication of the bridge output voltage. A probe actuator with appropriate switching arrangement was used to control the angular orientation of the hot-wire array with the air flow. The circuit employed in obtaining angle data, as well as the theory and procedure, is discussed in reference 3.

A compromise among wire sensitivity, effects of radial angle gradients, and wire life determined the size of the wires used for the investigation. A satisfactory wire life in the filtered-air supply limited the wire diameter to a minimum of 0.0009 inch. The wire length was kept small (0.045 in. or less) to reduce the effects of radial angle gradients. In spite of the small length, the extremely small wire diameter as compared with wire length resulted in a large wire length-to-diameter ratio and helped to increase the angle sensitivity and to minimize the effects of the supports on the wire operation. The wire operating temperature of approximately 250° C and wire spacing of 0.005 inch gave good sensitivity.

Wire damage from collision by dirt particles in the air supply either made the probe inoperative or changed the original wire orientation, thereby changing the reference-angle calibration. Frequent checking of a previous data point was therefore essential to prevent data errors resulting from change in wire orientation due to wire damage.

When the pair of heated wires was alined with the air stream, notation of the reversals of the change of bridge output voltage was made visually. Several reversals were usually made to obtain an accurate angle value. The variation in a set of readings was on the order of $\pm 0.5^\circ$ for most series.

V-wire probe. - The probe consisting of a radially mounted parallel pair of wires was thought to be unsuitable for boundary-layer measurements near the inner shroud, because large nonuniform radial angle gradients exist in this boundary layer and also because the wire length limits the minimum radial distance between survey point and inner shroud to about 0.035 inch. Therefore, a V-wire probe was constructed with wires of the same material as the parallel-wire probe mounted in a plane perpendicular to the probe axis and parallel to the shroud surface in the vicinity of the measuring point. In operation, a reproducible orientation of the wires with respect to the air-flow direction was obtained by rotating them about the probe axis until the resistance ratio of the two wires with convective heat loss due to the air stream was the same as their resistance ratio with no convective heat loss. The procedure involved obtaining an angle reading for this rotative position at a point where the flow direction was known and comparing angle readings at other points with this known angle.

The electrical equipment used with the V-wire probe was essentially the same as with the parallel-wire probe, except that the two wires were balanced against each other rather than against a constant resistance. Also, a sensitive galvanometer was used as an indicating instrument instead of the amplifier-voltmeter combination required for the parallel wires.

As in the use of the parallel wires, frequent checking of a previous data point was necessary to detect wire damage immediately and thereby avoid data errors.

APPENDIX B

SYMBOLS

The following symbols are used in the present report:

P_1	reference inlet total pressure, in. Hg
P	local total pressure, in. Hg
p	local static pressure, in. Hg
r	radius measured from axis, ft
V	local velocity, ft/sec
V_i	ideal velocity as determined by reference inlet total and local discharge static pressures, ft/sec
V_θ	local tangential velocity, ft/sec
γ	ratio of specific heats
η	local blade efficiency
ρ	static density, slugs/cu ft

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TABLE I - NOZZLE BLADE PROFILE COORDINATES

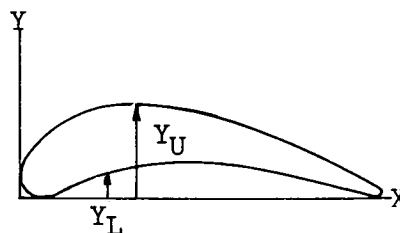
(a) Profile coordinates



X (in.)	Section					
	Root		Mean		Tip	
	Radius (in.)					
	5.939		7.003		8.122	
	Y _L (in.)	Y _U (in.)	Y _L (in.)	Y _U (in.)	Y _L (in.)	Y _U (in.)
0	0.0380	0.0380	0.0590	0.0590	0.0820	0.0820
0.100	.0322	.1826	.0156	.2164	.0023	.2376
.200	.0890	.2374	.0712	.2671	.0474	.2920
.300	.1297	.2635	.1086	.2922	.0870	.3200
.400	.1529	.2680	.1335	.2995	.1167	.3310
.500	.1599	.2566	.1474	.2931	.1377	.3288
.600	.1538	.2346	.1523	.2786	.1514	.3186
.700	.1385	.2063	.1494	.2587	.1585	.3034
.800	.1156	.1737	.1396	.2347	.1586	.2834
.900	.0872	.1377	.1241	.2070	.1526	.2599
1.000	.0550	.0990	.1044	.1766	.1416	.2343
1.100	.0198	.0583	.0816	.1449	.1268	.2074
1.172	.0170	.0170	-----	-----	-----	-----
1.200	-----	-----	.0564	.1119	.1090	.1796
1.300	-----	-----	.0296	.0783	.0889	.1516
1.400	-----	-----	.0013	.0439	.0669	.1234
1.428	-----	-----	.0200	.0200	-----	-----
1.500	-----	-----	-----	-----	.0433	.0952
1.600	-----	-----	-----	-----	.0185	.0670
1.696	-----	-----	-----	-----	.0220	.0220

(b) Stacking coordinates

X (in.)	Section		
	Root	Mean	Tip
	Y (in.)	Y (in.)	Y (in.)
0.065	0.074	-----	-----
.094	-----	0.102	-----
.122	-----	-----	0.130
.638	.192	-----	-----
.667	-----	.220	-----
.695	-----	-----	.248



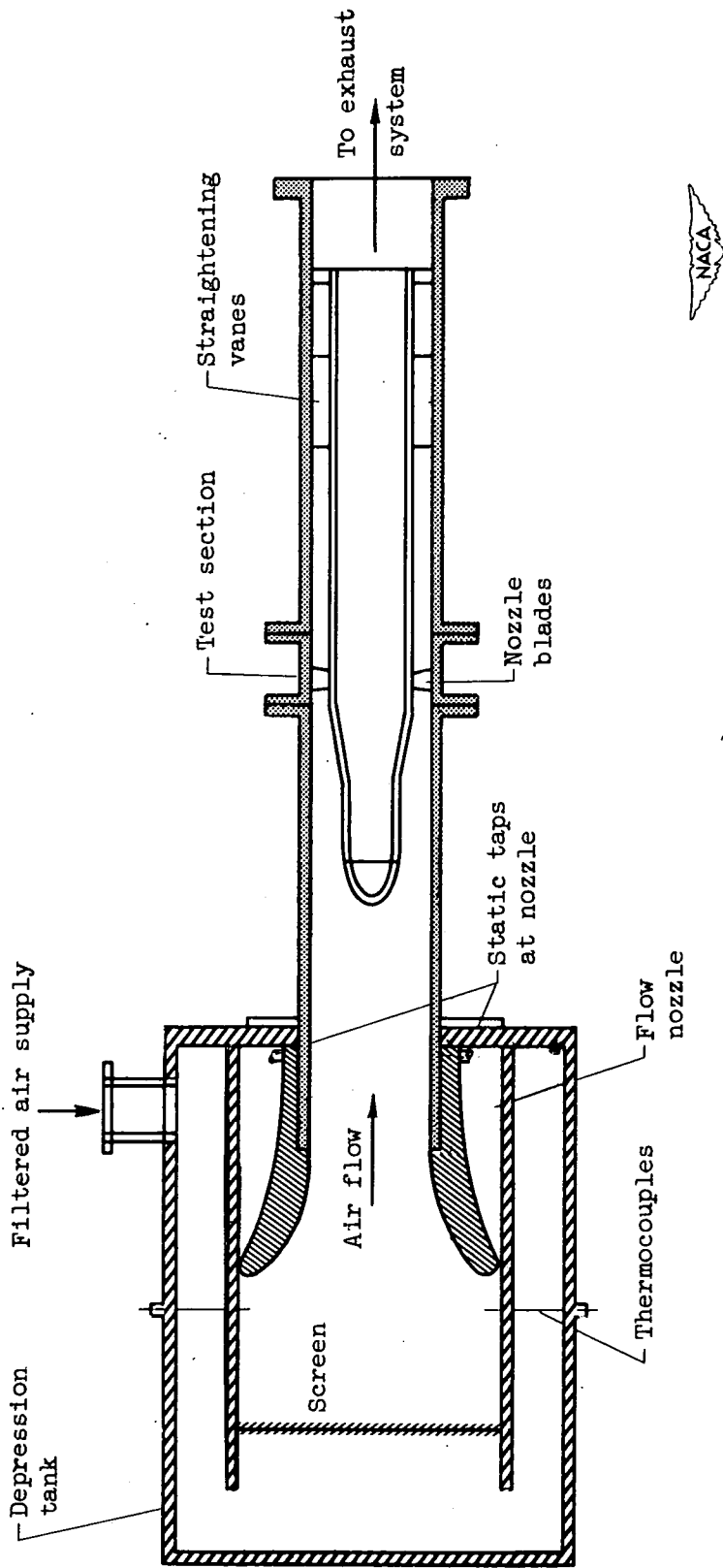


Figure 1. - Schematic view of annular nozzle cascade test unit.

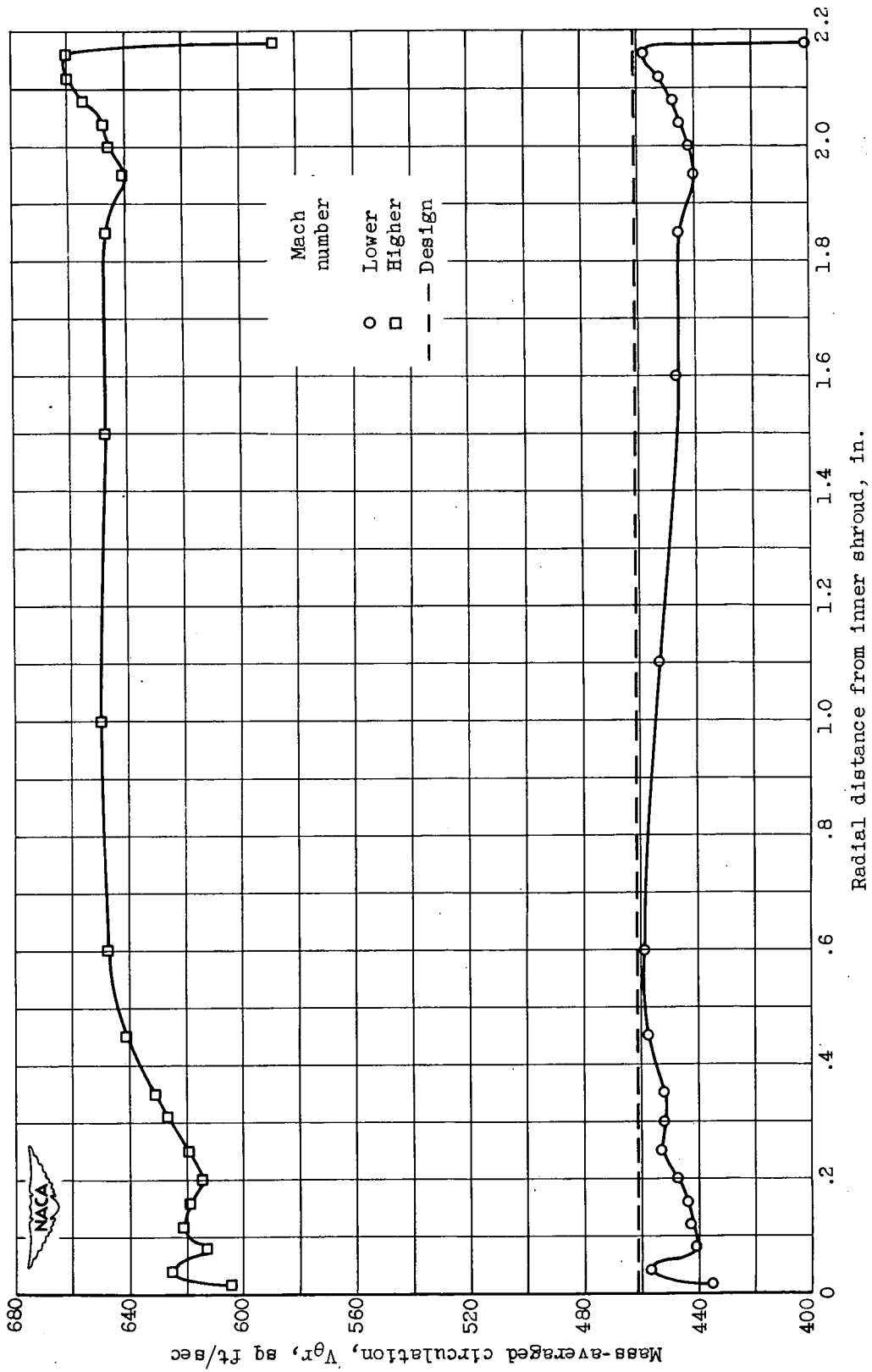
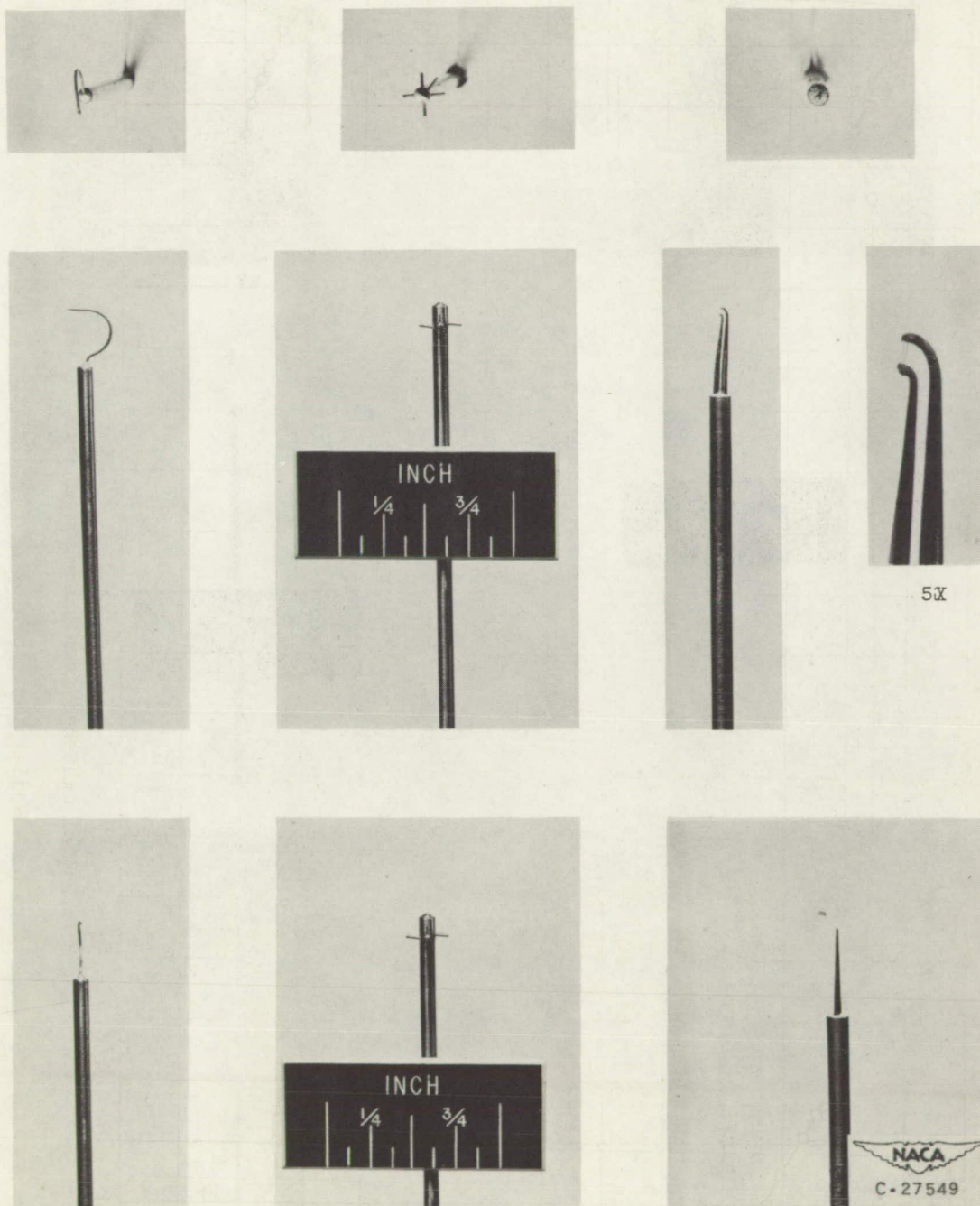


Figure 2. - Radial distribution of circulation.



(a) Boundary-layer probe.

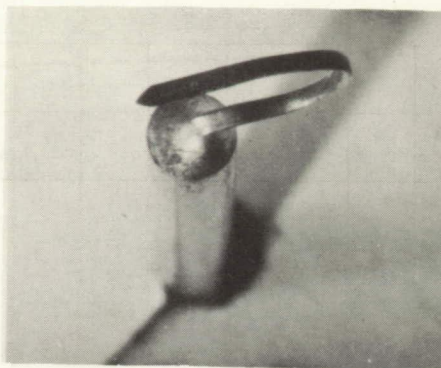
(b) Three-dimensional total-pressure probe.

(c) Parallel-wire-anemometer probe.

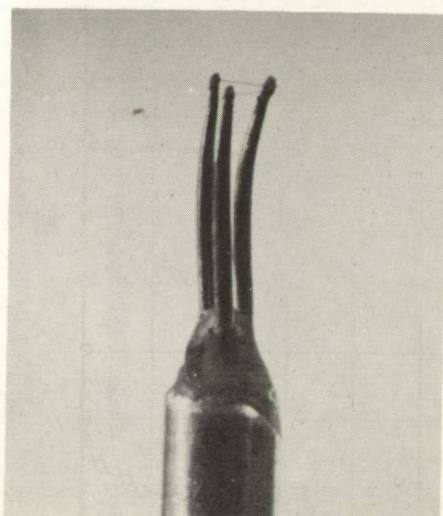
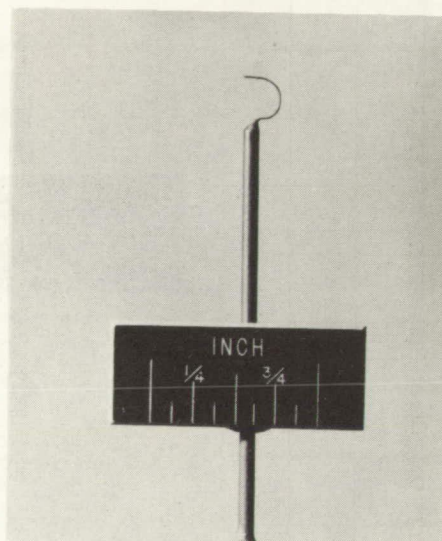
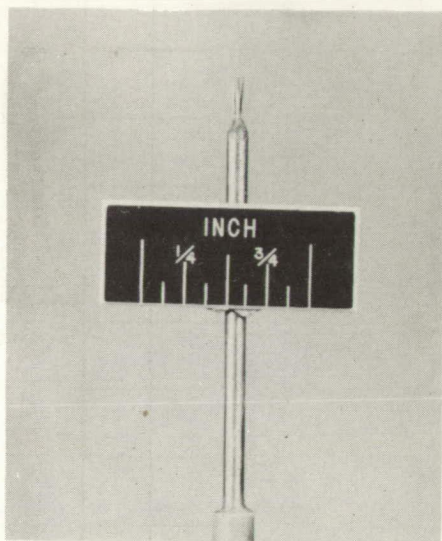
Figure 3. - Survey instruments.



5X



5X



5X

(d) V-wire-anemometer probe.



5X

(e) Double-tube angle probe.

Figure 3. - Concluded. Survey instruments.

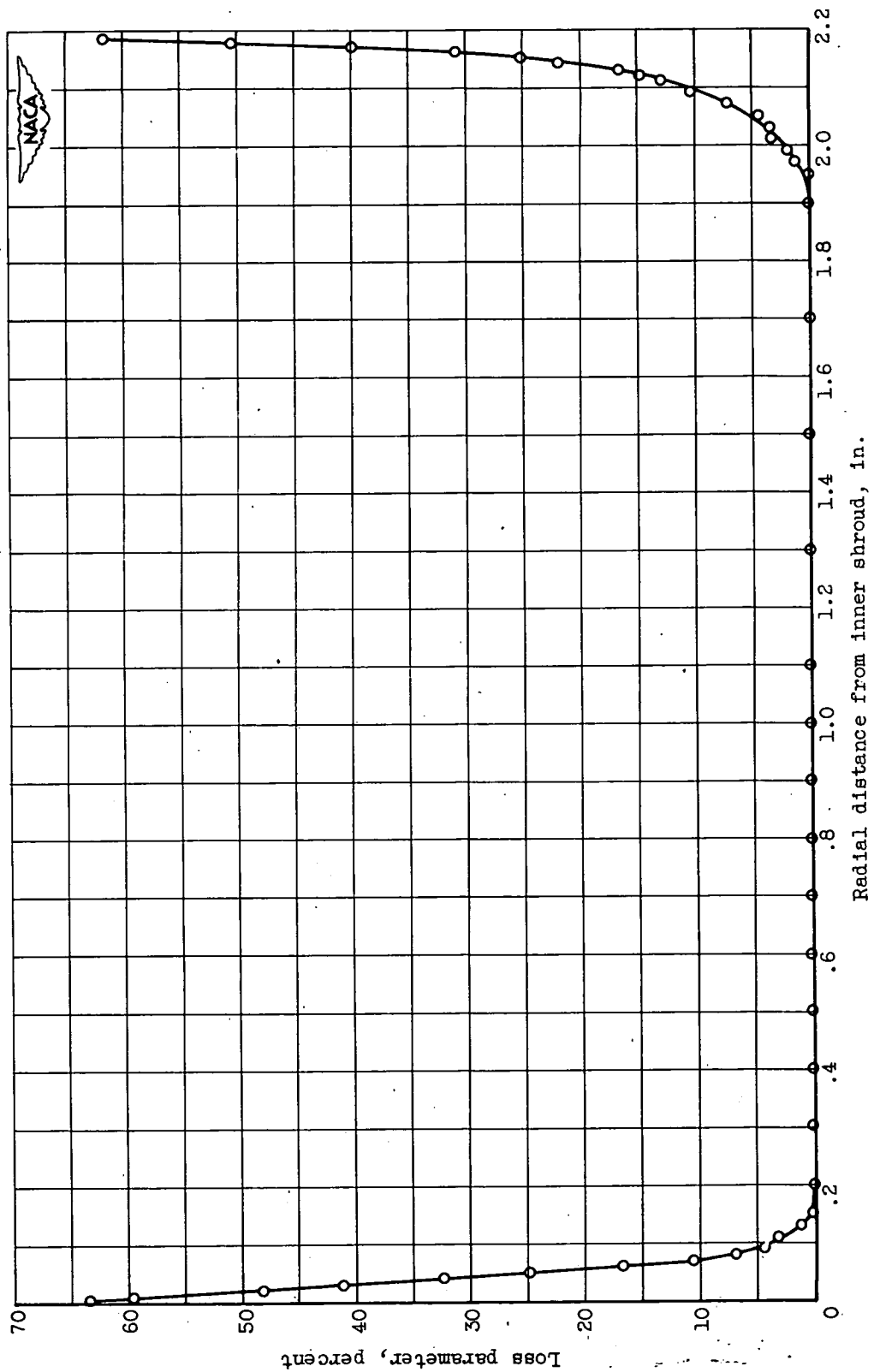
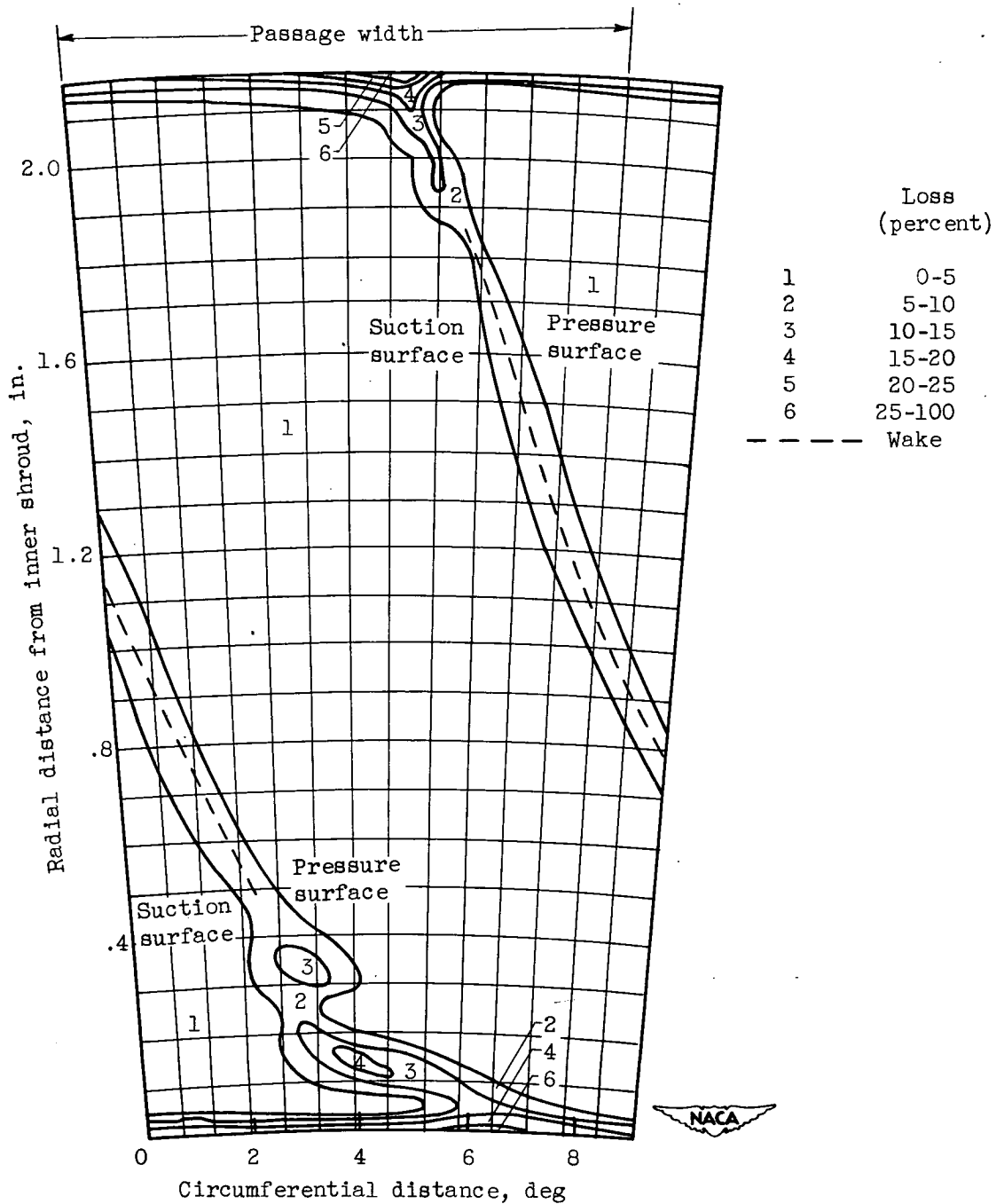
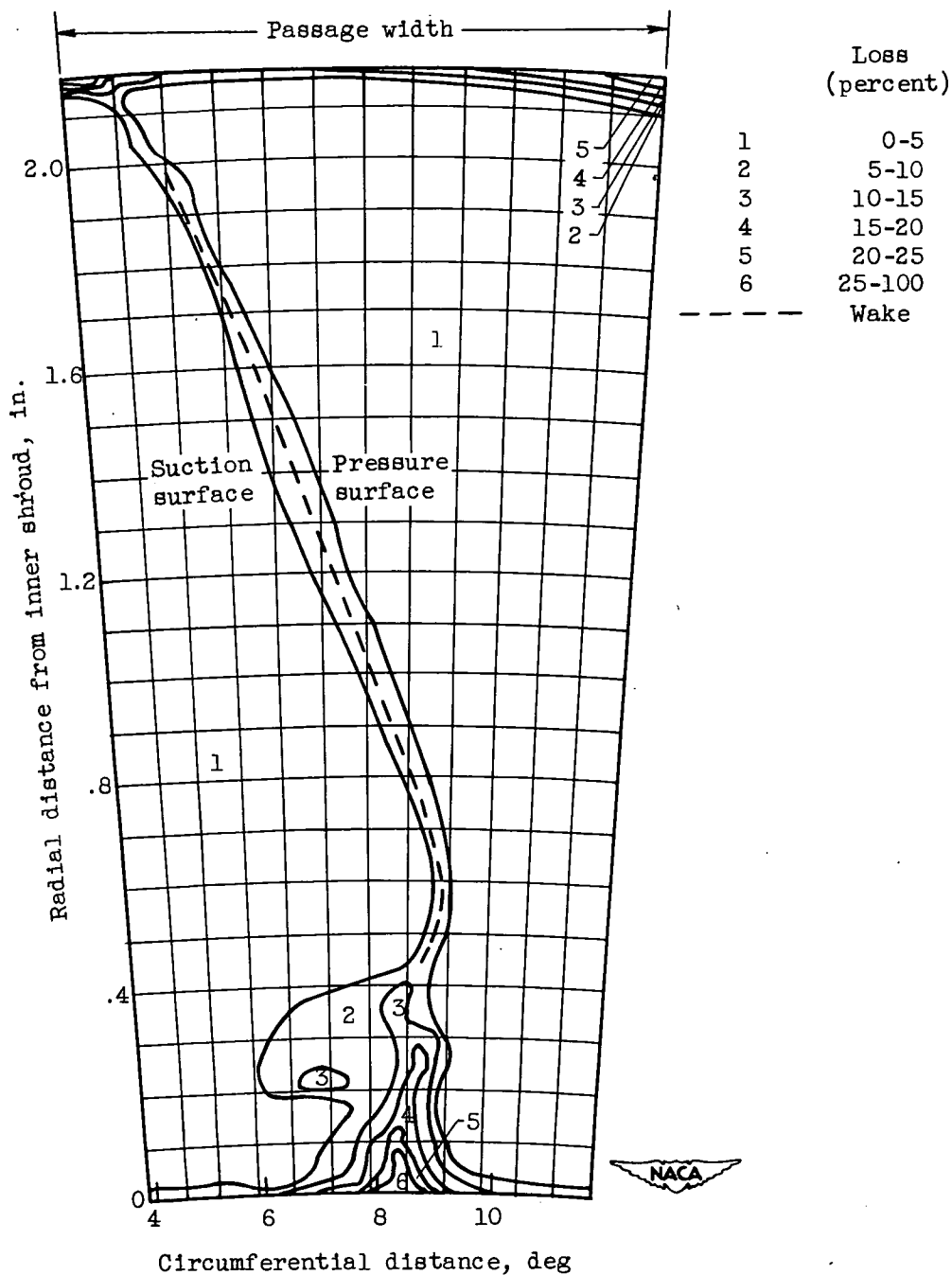


Figure 4. - Inlet loss distribution.



(a) Lower Mach number.

Figure 5. - Contours of loss across one blade passage.



(b) Higher Mach number.

Figure 5. - Concluded. Contours of loss across one blade passage.

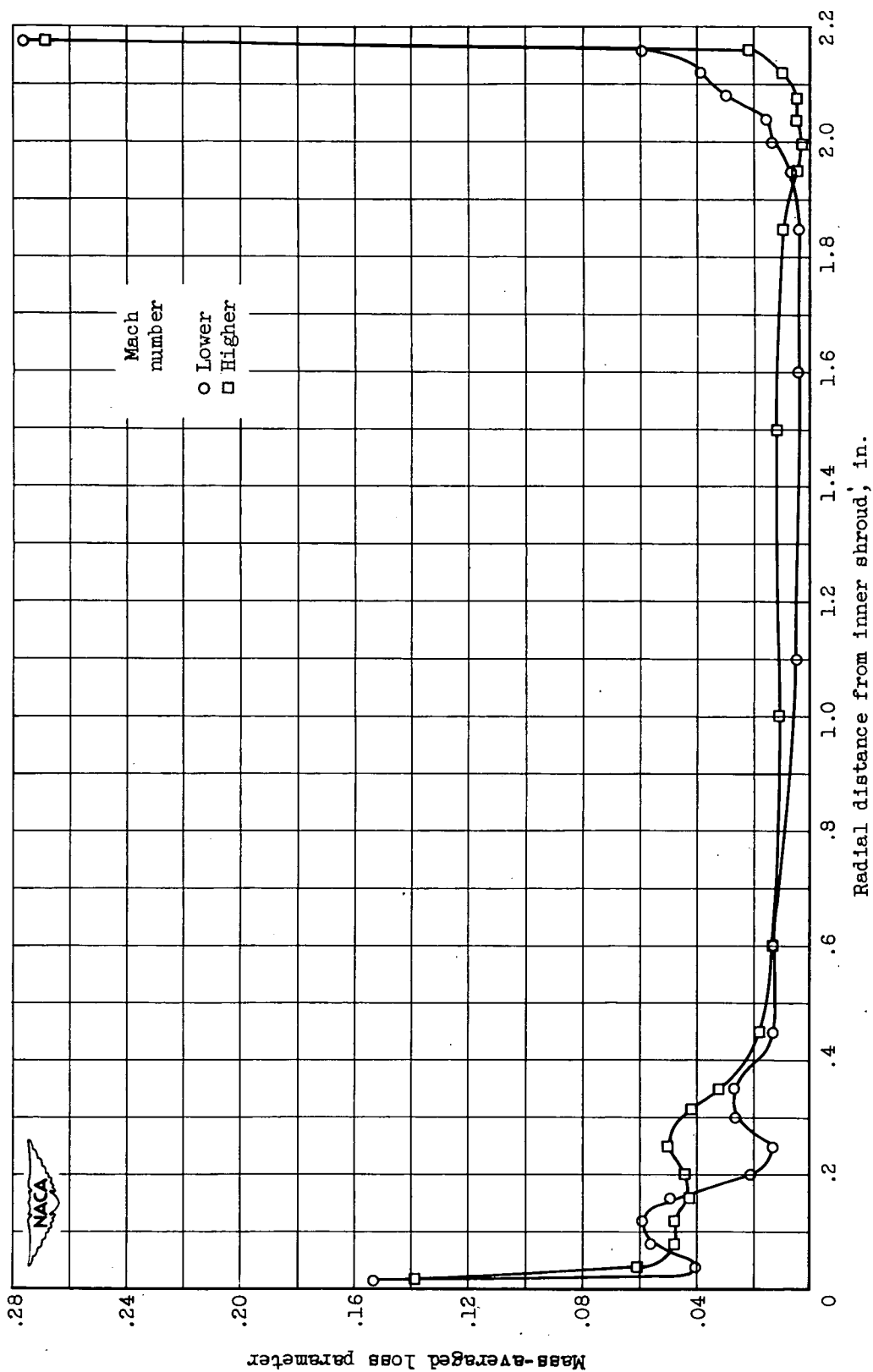
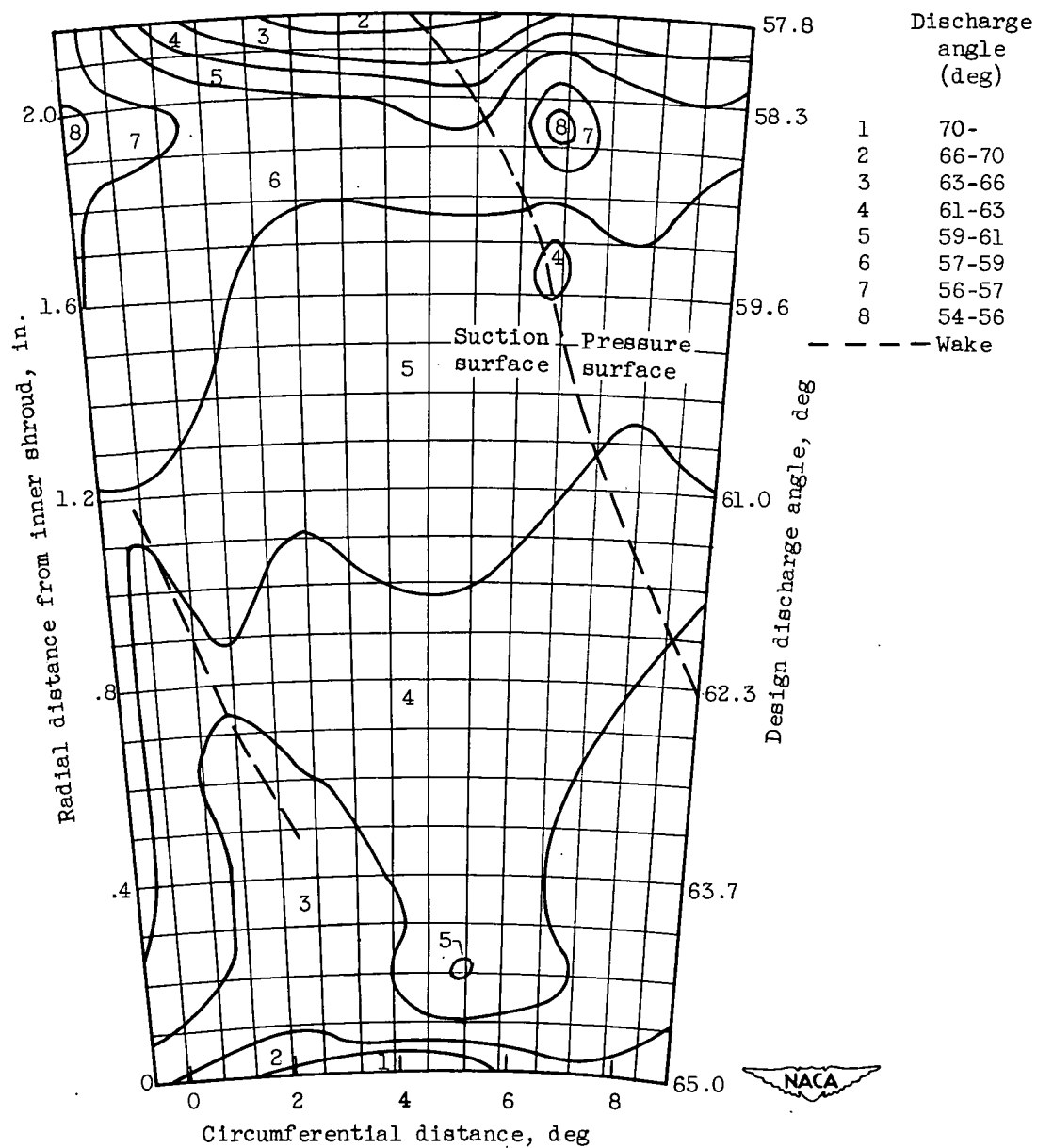
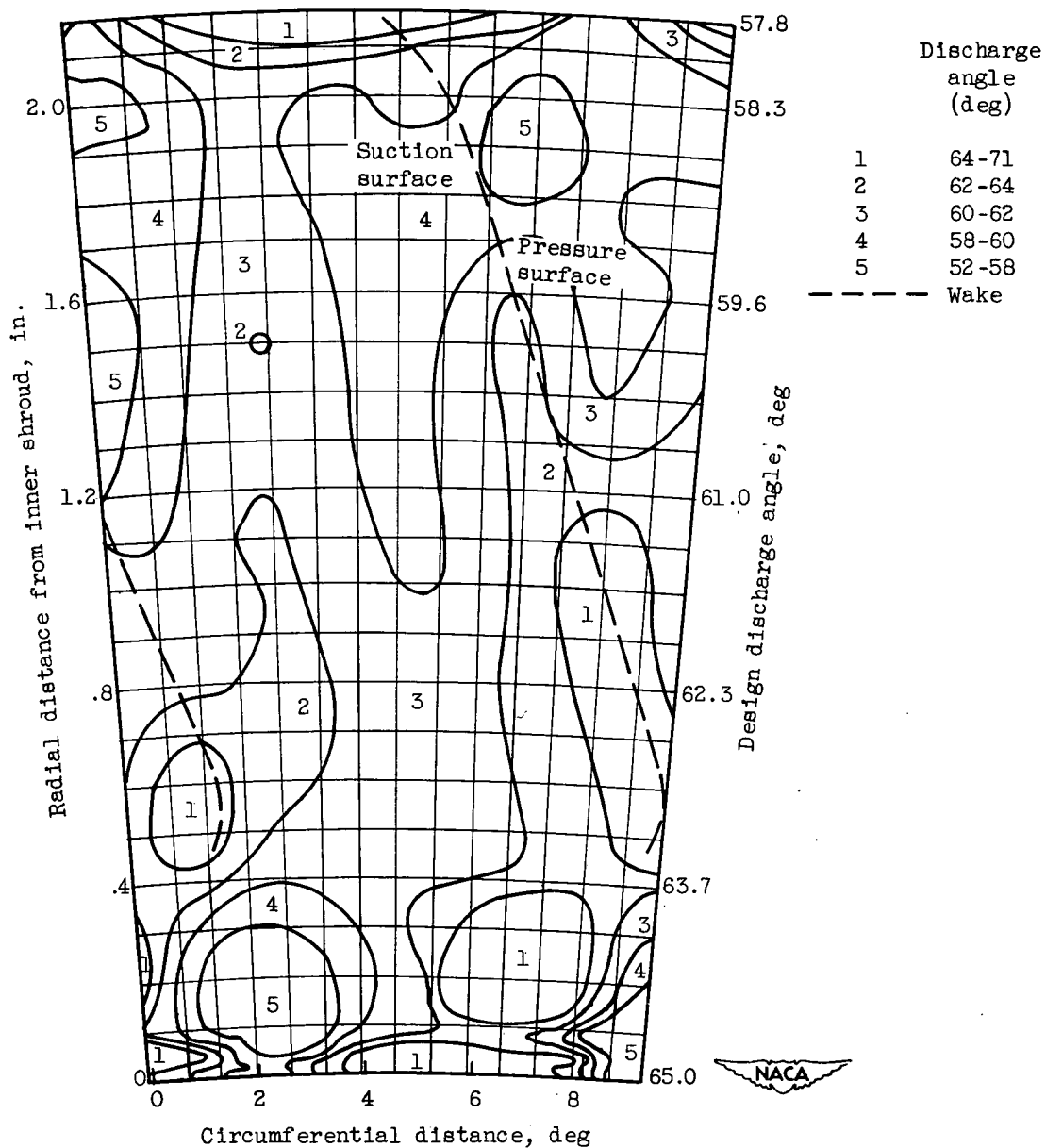


Figure 6. - Radial distribution of loss at nozzle discharge.



(a) Lower Mach number.

Figure 7. - Contours of discharge flow angle across one blade passage.



(b) Higher Mach number.

Figure 7. - Concluded. Contours of discharge flow angle across one blade passage.

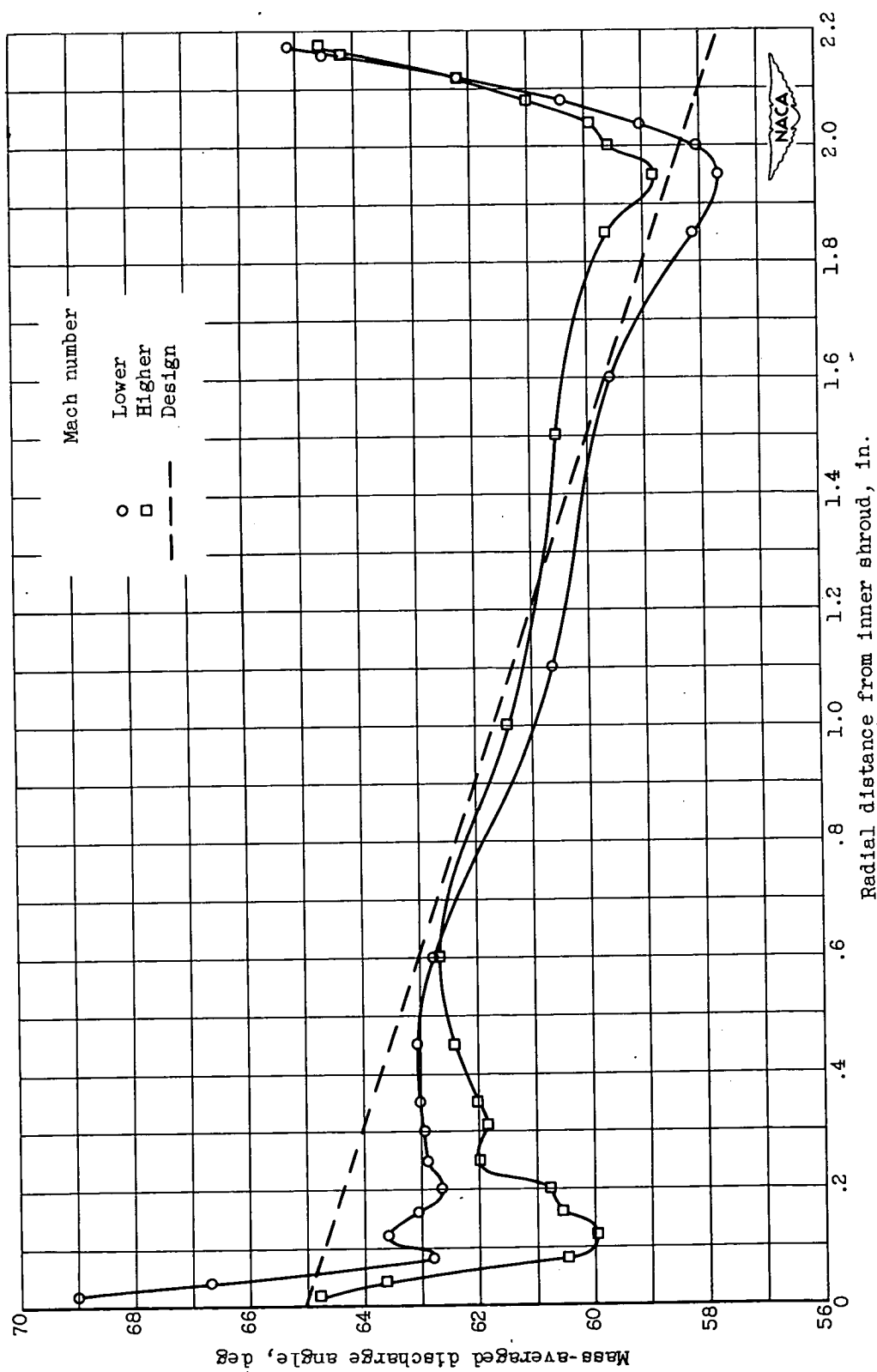
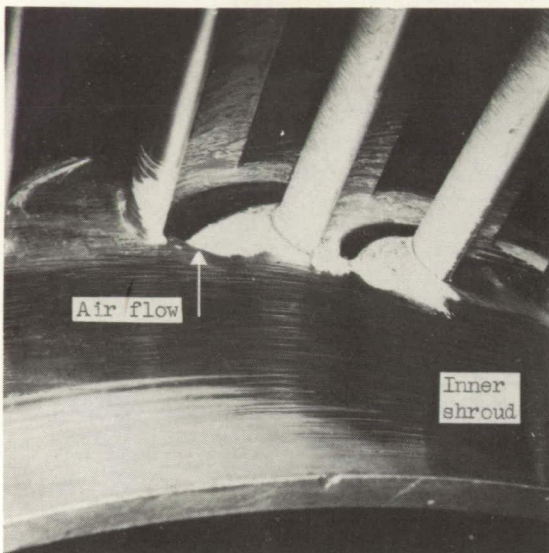
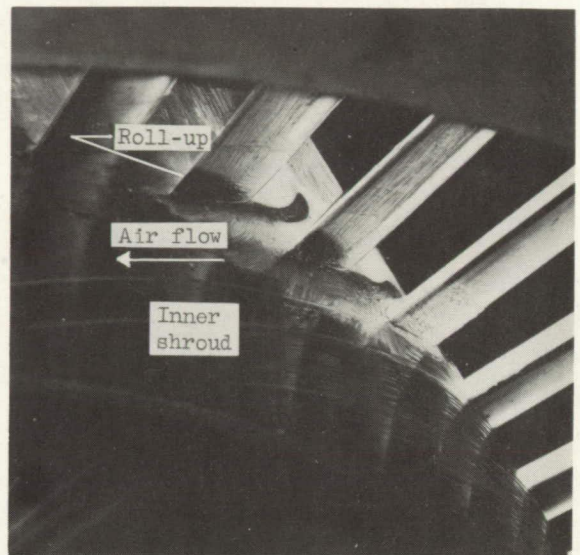


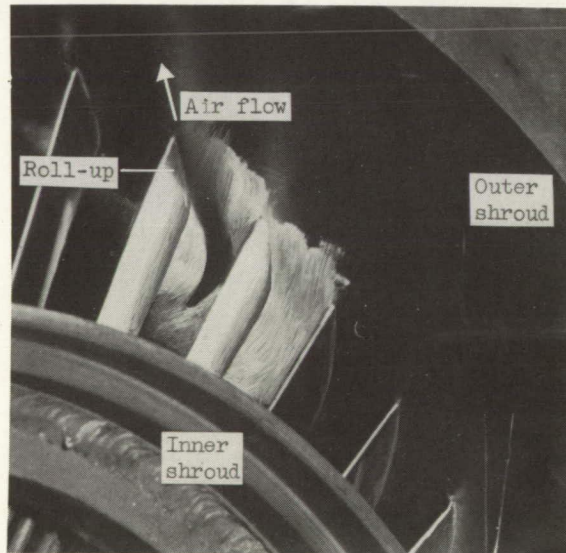
Figure 8. - Radial distribution of discharge angle.



(a) Inner shroud at inlet



(b) Inner shroud at discharge.



(c) Outer shroud at discharge.

Figure 9. - Hydrogen sulfide flow traces through blade channel.

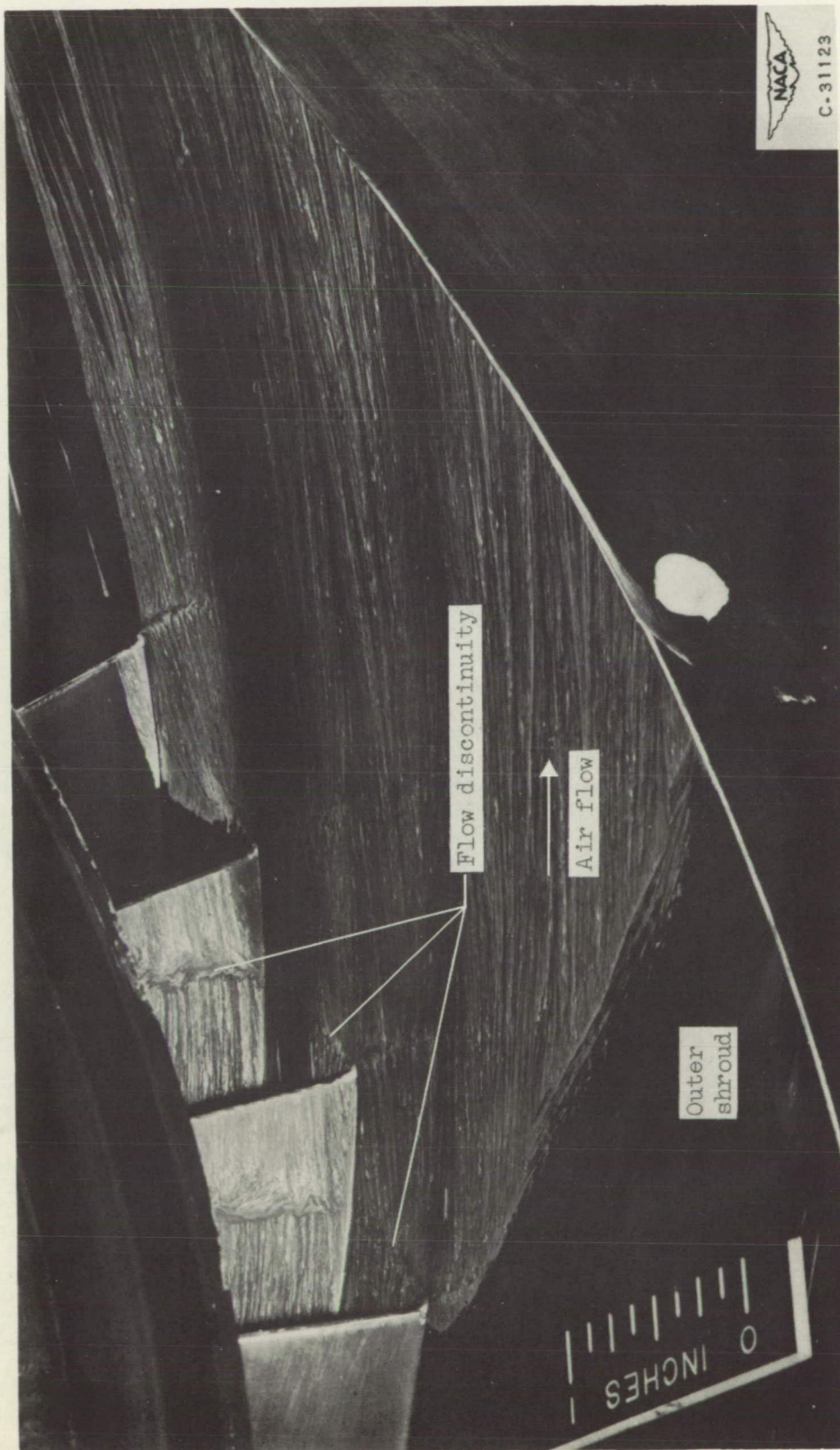
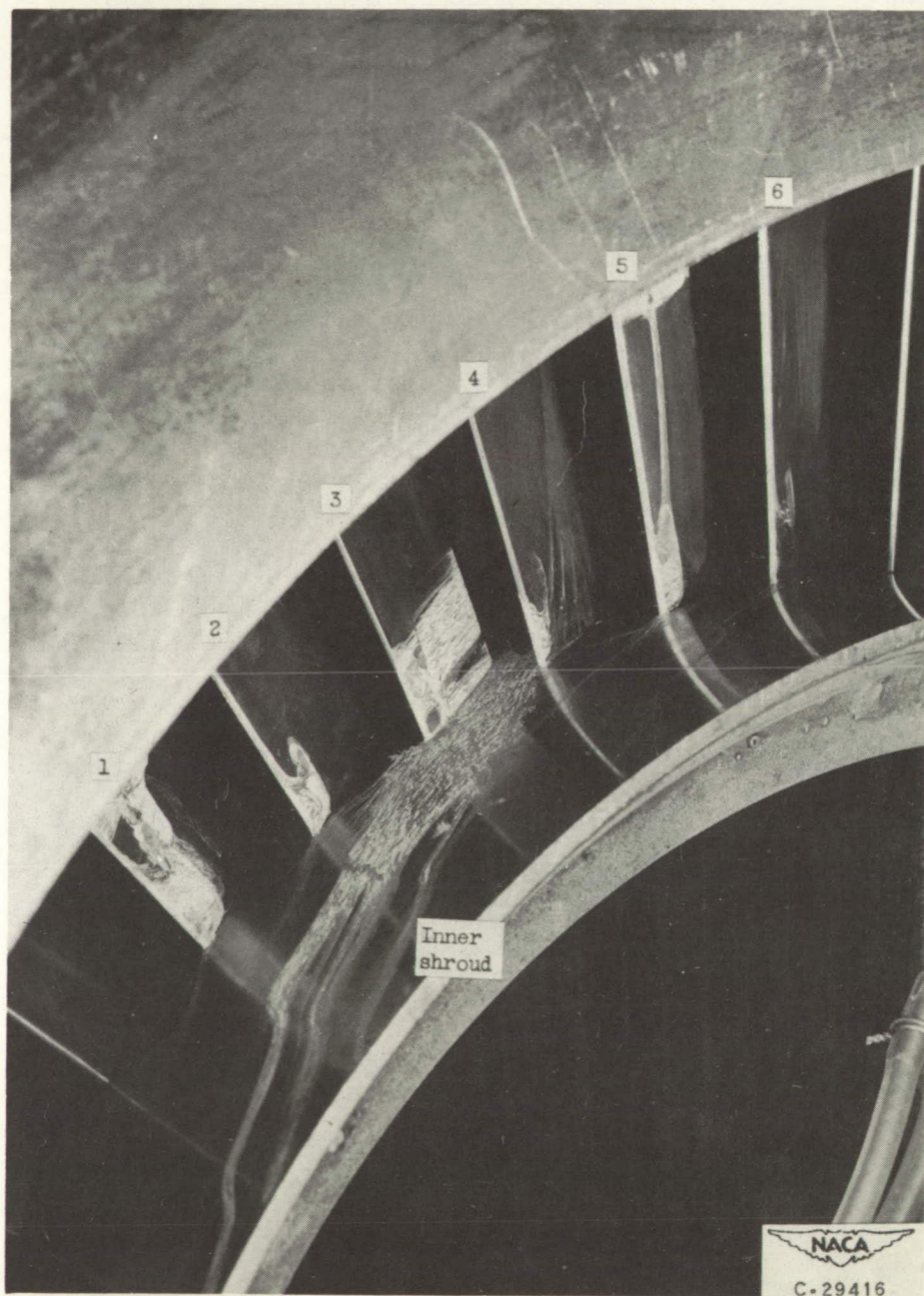
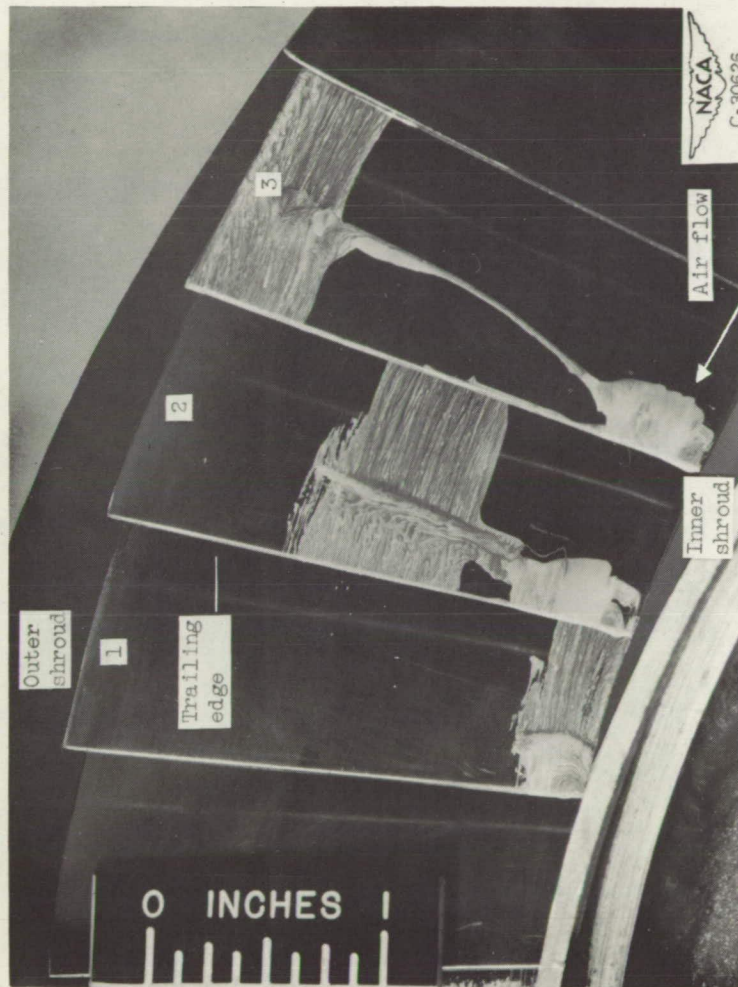


Figure 10. - Flow discontinuity at nozzle discharge.



(a) Indications of inward radial flow of low-momentum fluid.

Figure 11. - Paint traces of secondary flow along blade suction surface at nozzle discharge.



(b) Enlarged view of inward radial flow of low-momentum fluid.

Figure 11. - Concluded. Paint traces of secondary flow along blade suction surface at nozzle discharge.

NACA TN 2871

National Advisory Committee for Aeronautics.
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 Allen, Milton G. Kofskey and Richard E. Chamness.
 January 1953. 33p. diagrs., photos., tab.
 (NACA TN 2871)

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 Visual traces of shroud boundary-layer flow showed
 a cross-channel component of velocity and indicated
 one source to the accumulation of low-momentum

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 5. Boundary-Layer
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fluid comprising the loss region. Results of a shift of the loss region and visual indications of the boundary-layer flow along the blade surfaces at the higher Mach number showed that the low-momentum fluid originating on the outer shroud and blade surfaces flows radially inward through a thickened portion of the boundary layer on the blade suction surface and along the trailing edge in the wake of the blades.

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